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Effects of Defects on Failure of Butt Fusion Welded Polyethylene Pipe

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Abstract

Medium density polyethylene (MDPE) pipes are usually welded together by butt fusion welding. The quality of butt fusion welded MDPE pipe joints is seriously affected by welding defects sometimes. This paper presented the test results of an experimental tension test, burst test, three-point bend test, crush test, and fatigue test to show the effect of a single welding defect on the failure of butt fusion welded MDPE pipe joints. The fracture resistance of the joints without welding defects was studied by a fracture test too. The results showed that, under the tension, pressure, bend, and crush loadings, the defect could not increase the failure of the joints if the defect size was smaller than 15% of the pipe's wall thickness regardless of the defect geometry, but the defect increased the failure even though the defect size was only 15% of the pipe's wall thickness under the fatigue loading.

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*Keywords:*Medium density polyethylene, MDPE, defect, fusion welding

1. Introduction

Medium density polyethylene (MDPE) pipes are widely used in the past decades due to the characteristics of cost effectiveness, highly stable chemical structure and advantageous mechanical properties. They can also be simply and effectively welded together by butt fusion welding to create a good airproof and structurally sound pipe system. Therefore, they are conveniently applied to complicate structures, such as water and gas distribution pipe systems. Till now, a tremendous amount of work has been studied the butt fusion welding for polyethylene pipes. Moore [1]

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showed that the thermal stability of the polyethylene pipes was not affected by the welding. Ezrin[2]found that the mechanical properties of the welded polyethylene pipes, such as yield strength and elongation at fracture, were almost the same as the original pipes. Lee [3] indicated that the welding was an excellent method for robust joining for high density polyethylene pipes when the process conditions were judiciously designed. Lu [4] found that the effect of contaminants of Vaseline and graphite on the weld quality was negligible at high weld pressure. However, the failure of the butt fusion welded joint may be increased if there is welding defects, such as lack of fusion, shrinkage pores, and foreign matter inclusions [5].In addition, for a pipe system, its potentially subject to complex loading conditions including tension, bend, fatigue, crush, and creep, but there is not a systematic work to research the effect of welding defects on the failure of butt fusion welded MDPE pipe joints under various loading conditions.

In this paper, the effects of butt fusion welding defects on the failure of welded MDPE pipe joints were systematically studied by an experimental tension test, burst test, three-point bend test, crush test, and fatigue test. Defects were artificially inserted into the fused welding surface to simulate lack of bonding during fusion welding. Since the fracture toughness values measured from single edge notch tension [SE(T)] specimens seem more suitable to describe the fracture resistance of pressurized pipelines than those from deep notch fracture specimens under the bend loading employed in the ASTM E 1820standard [6],the SE(T) specimens without welding defects were also used to carry out fracture tests to study the fracture resistance of welded MDPE pipe joints.

Nomenclature

a	Crack length
A_{el}, A_{pl}	Elastic and plastic areas under the load-displacement curve, respectively
b_0	Original uncracked ligament
B	Thickness of the SE(T) specimen
H	Distance between two pins
J	Path-independent J-integral
J_{max}	J-integral at the maximum applied load
MDPE	Medium density polyethylene
O.D	Outside diameter of the MDPE pipe
W	Width of the SE(T) specimen
t	Pipe's wall thickness
η_{el}, η_{pl}	Nondimensional parameters describing the elastic and plastic contribution to the strain energy, respectively
ξ_0–ξ_5	Nondimensional coefficients

2. Experimental material and procedures

MDPE pipes had three outside diameters (O.D) of 110, 225, and 315 mm.The standard dimension ratio (SDR) was 11, meaning that the ratio of the O.D to the thickness (t) was 11. The material density and melt flow index were 939 kg/m^3 and 0.2 g/10 min, respectively. Pipe joint manufacturing using butt fusion welding was conducted according to the ISO 21307 standard [7]. Defects were artificially inserted atthe center of the butt-weld surface before heating for fusion.Figure 1showsthat a defect was inserted into a previous shallow drilling defect location, and then the pipes were welded together by butt fusion welding. The defects were made of steel in two different geometries, i.e., planar andspherical defects, to simulate the lack of bonding during the welding as shown in Fig. 1(a). All defects were located at the center of the cross section area of the weld. The dimensions of all defects and pipes are shown in Table 1. The ratios of the defect size to the pipe's wall thickness were 15, 30, and 45%, respectively. The typical test specimens were shown in Fig. 2. The welding bead was retained to simulate actual application situations and a single welding defect was located in the middle and the12 o'clock position for all specimens except the SE(T) specimens of fracture tests. All tests were carried out at room temperature [8].

All tension test specimens weremachined out from the welded MDPE pipe joints and prepared according to the DVS 2203-2 standard [9]. One of the specimens (O.D = 225 mm) is shown in Fig 2(a). The engineering stress-strain curves of the specimens were recorded during the tests.

(a) (b)

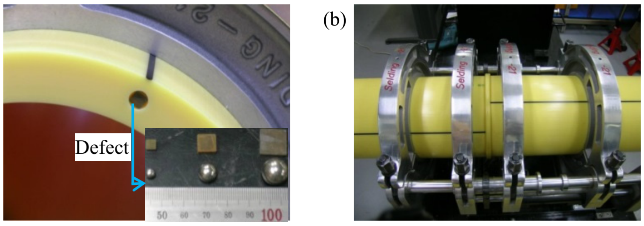


Fig. 1. (a) Inserting a defect (ball or plate) into a previous shallow drilling defect location; (b) Butt fusion welding and cooling.

Table 1. Dimensions and geometries of the defects inserted in pipe joints

Pipe Size		Spherical Defect		Planar Defect	
Outside Diameter (mm)	Thickness (mm)	Ball Diameter (mm)	Ball Diameter/Thickness(%)	Width×Length×Depth (mm×mm×mm)	Width/ Thickness (%)
110	10	0	0	0	0
		1.5	15	1.5×1.5×1.0	15
		3.0	30	3.0×3.0×1.0	30
		4.5	45	4.5×4.5×1.0	45
225	20	0	0	0	0
		3.0	15	3.0×3.0×1.0	15
		6.0	30	6.0×6.0×1.0	30
		9.5	45	9.5×9.5×1.0	45
315	29	0	0	0	0
		4.5	15	4.5×4.5×1.0	15
		8.7	30	8.7×8.7×1.0	30
		12.7	45	12.7×12.7×1.0	45

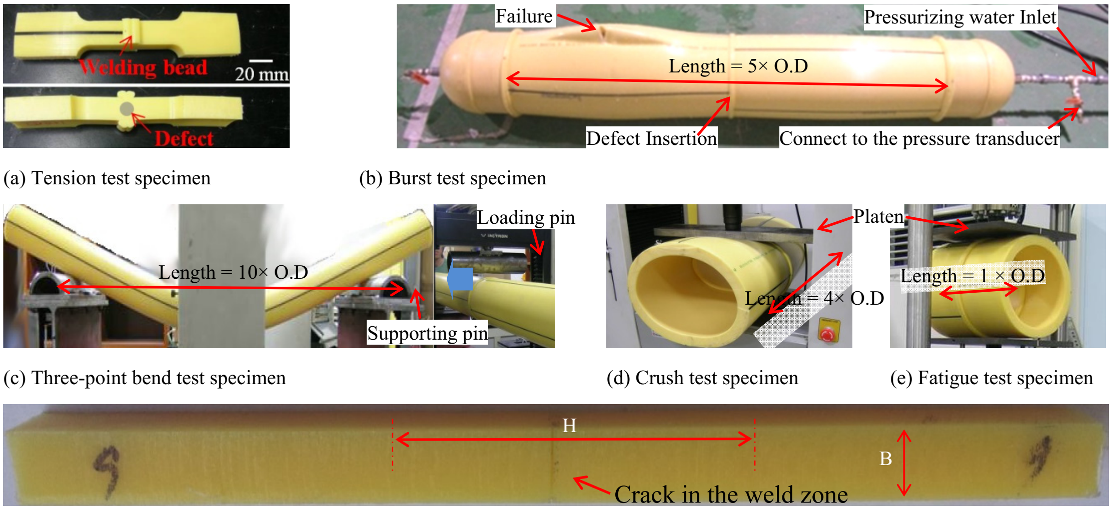
The specimens with burst tests were prepared and conducted according to the ASTM D 1599 standard [10]. Figure 2 (b) shows one of the specimen failures (O.D = 315 mm). Both ends of the specimen were closed with hemi-spherical end caps by butt fusion welding. The specimen length between the two end closures was five times the O.D.The applied pressure and the time were monitored during the tests.

The three-point bend test is shown in Fig (c). The span length of the specimen was equal to ten times the O.D and the diameter of the loading pin and supporting pin was 100 mm.

The crush test is shown in Fig. 2 (d). The specimen length was four times the O.D. The width of the platen was 30 mm. For both of the three-point bend test and the crush test, the applied displacement speed of the loading pin and the platen was 20 mm/min, and the applied load and the displacement were recorded during the tests.

For each of the above mentioned tests, three identical specimens were tested for each size of the welded MDPE pipe joints. Therefore, tests were conducted in 21 specimens for each pipe size as shown in Table 1 (2 defect geometries × 3 defect sizes × 3 specimens + 3 no defect specimens). A total of 63 specimensweretested for each of the above mentioned tests, becausethree pipe sizes were studied.

The fatigue test is shown in Fig. 2 (e). Only two specimens with 315 mm O.D were tested, the specimen without defects and the specimen with a spherical defect that was 15% of the thickness. The specimen length was equal to the O.D. Fatigue tests were performed using a testing frequency of 1 Hz, with the force controlled with constant sinusoidal force amplitude. The maximum force of 11.27 KN caused 5% O.D compression deformation of the specimen without defectsafter it was compressed by the platen. The minimum force was 0.1 times as large as the maximum force. Thus, the *R*-ratio, the ratio of the minimum load to the maximum load in the fatigue loading cycle, was 0.1. The displacement of the platen and the fatigue cycle were measured during the test.



(a) Tension test specimen (b) Burst test specimen

(c) Three-point bend test specimen (d) Crush test specimen (e) Fatigue test specimen

(f) Fracture test [SE(T)] specimen

Fig. 2. Typical test specimens.

One of the SE(T)specimens without welding defects is shown in Fig. 2 (f) machined out from the welded MDPE pipe joints in the axial direction. The weld zone was located in the middle of the specimen, and the crack was at the center of the weld zone.The dimensions of the specimen were the thicknessB= 10 mm, the width W = 10 mm,the distance between the twopinsfor measurement of theload-displacement H = 50 mm, andthe total length =140 mm. The crack was made carefully by pushing a fresh razor blade at a cutting rate of 8 mm/min to form a sharp crack from the surface of the specimen at room temperature. The crack ratio of the crack length, a, to theW was from 0.1 to 0.5 with increments of 0.1 and each value of a/W had two specimens. Therefore, a total of 10 specimens without welding defectsweretested. All the tests were carried out by an Instron testing machine at a constant crosshead speed of 2 mm/min. The applied load and the displacement were recorded during the tests.

3. Results and discussion

3.1. Tension test

The test results of engineering stress-strain curves obtained from the specimens with 110 and 315 mm O.D are shown in Fig. 3. Note that each curve shown in Fig. 3 was the average curve of three curves, because three identical specimens were tested for each defect size. The results of the specimens with 225 mm O.D were similar as those with110 and 315 mm O.D. Thus, they were not shown in Fig. 3. For the specimens with 110mm O.D, as shown in Fig. 3 (a), the curves of the no defect specimen and the defect specimens with defect size of 15% of the thickness were almost same regardless of the defect geometry. While the curves of the defect specimens decreased rapidly after they came to the maximum value for the defect size increased up to 30 and 45 % of the thickness. The effect of the defect geometry on the curve was hard to be distinguished. This means that the effect of the defect geometry on the failure of the joints was ignorable. Fig. 3 (b) shows the curves of the specimens with 315 mm O.D. The curves of the no defect specimen and the defect specimens with defect size of 15% of the thickness almost had the same variation trend, but the failure strain of the no defect specimen was quite smaller than that of the spherical defect specimen with defect size of 15% of the thickness. This was possibly caused by the test data scatter. With increased the defect size to 30 and 45 % of the thickness, the curves decreased rapidly after they came to the maximum value. Therefore, a single welding defect can't affect the failure of the welded MDPE pipe joints under the tension loading if the defect size is smaller than 15% of the thickness regardless of the defect geometry. The more detailed analyses can be found in the reference [11].

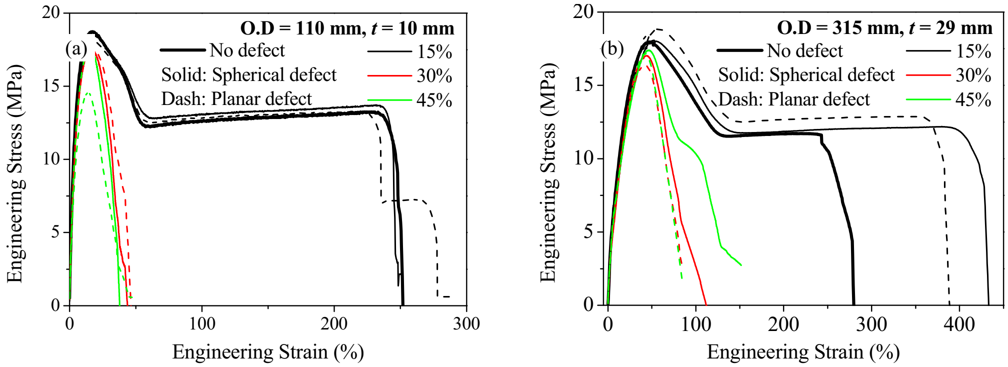


Fig. 3. Tension test results.

3.2. Burst test

Figure 4 shows the burst test results of pressure-time curves for the specimens with 100 and 315 mm O.D. Each curve shown in Fig. 4 was the average curve of three curves and the curves of the specimens with 225 mm O.D were not shown in Fig. 4; the reasons were the same as those of tensile tests. As shown in Fig. 4, all curves had almost the same shape before they came to the maximum pressure. There was a variation block for the curves after the failure time. The failure time was defined as the time that the pressure began to decrease rapidly, as shown in Fig. 4 (a).For the specimens with 110 mm O.D, the curves of the defect specimens were always lower than that of the no defect specimen after the failure time. However, this phenomenon could not be found for the specimens with 315 mm O.D. Thus, this difference could possibly be caused by the test data scatter. The same as the tension test results that the effect of the defect geometry on the burst failure of the specimen was not observed. The maximum pressure and the failure time for the specimens of each pipe size were almost same, even though the curves of the defect specimens were lower than that of the no defect specimen after the failure time for the specimens with 110 mm O.D. Therefore, it can be argued that the failure of the welded MDPE pipe joints cannot affected by a single spherical or planar welding defect under the pressure loading even when the defect size is up to 45% of the thickness.

3.3. There-point bend test

The three-point bend test results of load-displacement curves are shown in Fig. 5. Each curve shown in Fig. 5 was also the average curve of three curves. As shown in Fig. 5, both of the spherical and planar defect specimens curves were distributed around that of the no defect specimen for each pipe size. This distribution was not induced by the defect size and the defect geometry, but by the reasonable test data distribution. Therefore, a single spherical or planar welding defect could not increase the failure of the welded MDPE pipe joints under the bend loading even when the defect size was increased up to 45% of the thickness.

3.4. Crush test

The crush test results of load-displacement curves are shown in Fig. 6. Each curve shown in Fig. 6 consists of the average curve of three curves.The curves of the spherical and planar defect specimens were distributed around that of the no defectspecimen for each pipe **size, as** shown in Fig. 6. This phenomenon is the same as that shown in Fig. 5of the three-point bend test results. Therefore, neither the single spherical nor the single planar welding defectcould increase the failure of the welded MDPE pipe joints under the crush loadingeven when the defect size was increased up to 45% of the thickness.

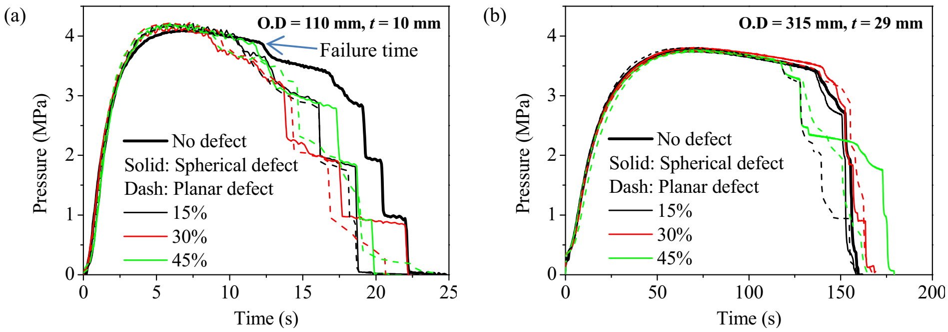


Fig. 4. Burst test results.

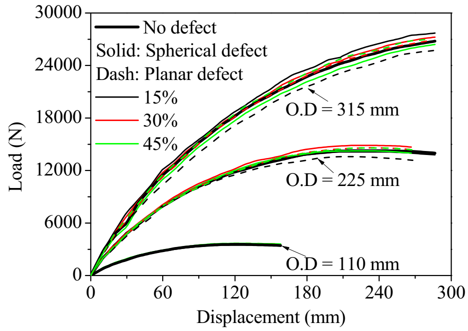


Fig. 5. Three-point bend test results.

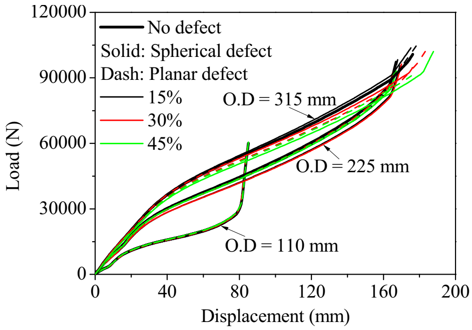


Fig. 6. Crush test results.

3.5. Fatigue test

The fatigue test results are shown in Fig. 7.The platen displacement was normalized by 2.5% O.D (7.9 mm). As shown in Fig. 7, the two curves overlapped at the beginning of the test. However, with increases in the fatigue cycle the curve of the no defect specimen decreased slowly to the first lowest value. After that, the curve decreased in waves with further increases in the cycle. The curve of the spherical defect specimen with defect size of 15% of the thickness decreased faster and to a lesser degree than did the curveof the no defect specimen with increasesin the cycle; this curve for this defect specimen also decreased in waves after attaining its first lowest value. This phenomenon of decrease in waves was the stepwise failure mechanism of polyethylene [12, 13]. The curve of the no defectspecimen was about double high that of the spherical defect specimen withdefect size of 15% of the thickness. This means that the fatigue performance of the tested welded pipes during the fatigue testswas significantly reduced by the welding defect. This result is similar as the effect of the large voids and inclusions that are produced during manufacture in the pipe wall on the fatigue performanceof polyethylenepipes [14]. Even though the number of data points was limited, we could deduce that the larger the defect size was, the lower the curve become. Thus, a single welding defect can significantly increase the failure of the welded MDPE pipe joints under the fatigue loading even for a small welding defect, such as that the defect size is 15% of the thickness.

3.6. Fracture test

The fracture of elastic-plastic materials is normally characterized by the path-independent J-integral. The J-integral can be calculated by:

$$J = \frac{\eta_{el} A_{el}}{B b_0} + \frac{\eta_{pl} A_{pl}}{B b_0} \tag{1}$$

where A_{el} and A_{pl} are the elastic and plastic areas under the load-displacement curve, respectively, η_{el} and η_{pl} are the nondimensional parameters describing the elastic and plastic contribution to the strain energy, respectively, and, b_0 is the original uncracked ligament.

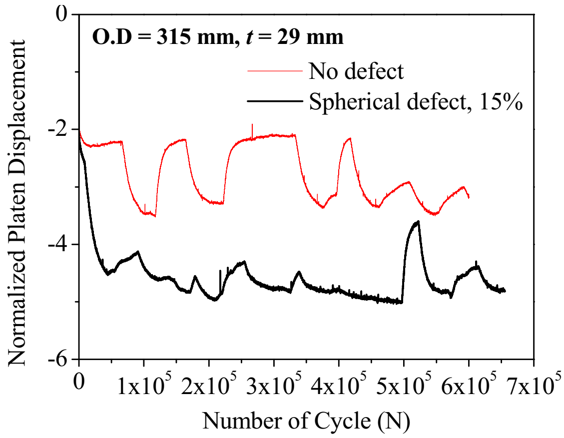


Fig. 7. Fatigue test results.

The measured load-displacement curves for all specimens are shown in Fig. 8 (a). In these tests, the crack extension length was not measured during the test and only two specimens were tested for each value of a/W. Therefore, the *J-R* curve could not be obtained from the test data by using the basic test method and the resistance curve test method [6]. If we assumed $\eta_{el} = \eta_{pl}$, the *J*-integral at the maximum applied load (the maximum load in the load-displacement curve), J_{max}, could be approximately calculated using the total area under the load-displacement curve. Ruggieri [15] showed that the η_{pl} of the homogeneous SE(T) specimencould be estimated by:

$$\eta_{pl} = \xi_0 + \xi_1 (a/W) + \xi_2 (a/W)^2 + \xi_3 (a/W)^3 + \xi_4 (a/W)^4 + \xi_5 (a/W)^5 \tag{2}$$

where the nondimensional coefficients of ξ_0–ξ_5 are dependent on the parameters of n and H/W. Eq.(2) is valid for $0.2 \leq a/W \leq 0.7$. Even though Paredes [16] showedthat the η_{pl} should be modifiedfor weld cracks, the effect of the weld zone on the η_{pl} was not considered in this paper. The calculated J_{max} are shown in Fig. 8 (b). The J_{max} was not calculated for $a/W = 0.1$, because the η_{pl} could not be calculated by Eq.(2).Figure 8 (b) shows that the J_{max} almost increased linearly with increases in the crack ratio from0.2 to 0.5.

In conclusion, the tension test, burst test, three-point bend test, crush test, and fatigue test are short-term tests. They can only test the short-term mechanical performance of MDPE pipes. Based on the results of these tests, it is argued that if there is no fatigue loading, a single welding defect with a maximum size that is less than 15% of the pipe's wall thickness cannot increase the failure of the butt fusion welded MDPE pipe joints under the short-term usage regardless of the defect geometry; otherwise, the defect can significantly increase the failure of the joints even for a small welding defect, such as that the defect size is 15% of the thickness. Since the room-temperature fatigue test can predict the long-term mechanical performance of polyethylene pipes [17-18], it is argued that a small single welding defect can significantly increase the failure of the joints under the long-term usage.

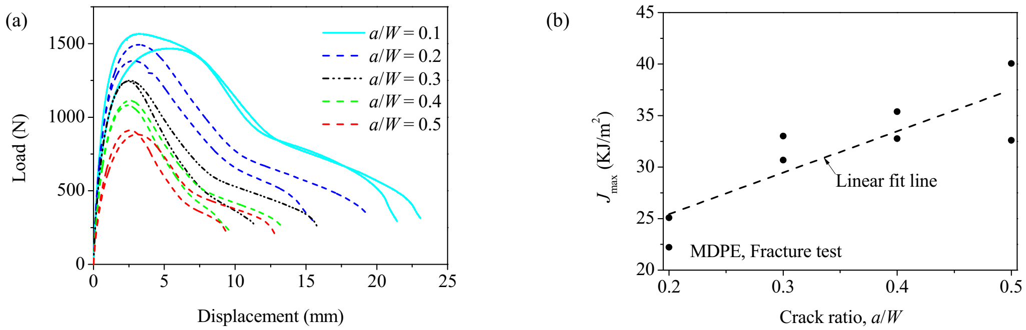


Fig. 8. Fracture test results: (a) measured load-displacement curves; (b) J_{max} under various crack ratios.

4. Conclusions

The effect of a single welding defect on the failure of butt fusion welded MDPE pipe joints were evaluated by an experimental tension test,burst test, three-point bend test, crush test, and fatigue test. The fracture resistance of the welded joints without welding defects was studied by a fracture test also. The following conclusions were reached:

(1) Based on the test results of the tension test, burst test, three-point bend test, crush test, and fatigue test, it is argued that if there is no fatigue loading, a single welding defect with a maximum size that is less than 15% of the pipe’s wall thickness cannot increase the failure of the butt fusion welded MDPE pipe joints under the short-term usage regardless of the defect geometry; otherwise, the defect can significantly increase the failure of the joints.

(2) The fatigue test showed that the fatigue performance of the butt fusion welded MDPE pipe jointswas significantly reduced by a single spherical welding defect, even though the defect size was only 15% of the thickness. Since the long-term mechanical performance of polyethylene pipes can be predicted by the fatigue test, it is argued that a single welding defect can significantly increase the failure of the joints under the long-term usage.

(3) The fracture test indicated that the *J*-integral at themaximum applied load almost increased linearly with increases in the crack ratiofrom0.2 to 0.5.

Acknowledgements

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References

[1] L.M. Moore,G.P. Marshall, N.S. Allen, Thermal analysis of MDPE pipe: A critical view,Polym.Degrad.Stabil. 25 (1989) 161–180.
[2] M. Ezrin, Plastic failure guide-cause and prevention,Munich,Hanser, 1996.
[3] B.Y. Lee,J.S. Kim,S.Y. Lee, Y.K. Kim, Butt-welding technology for double walled polyethylene pipe, Mater.Des.35 (2012) 626–632.
[4] X. Lu, R. Qian, N. Brown, G. Buczala, The effect of pressure and contaminants on slow crack growth in a butt fusion in a polyethylene gas pipe, J. Appl. Polym. Sci. 46 (1992) 1417–1427.
[5] DVS 2202-1, Imperfections in thermoplastic welded joints – Features, description, evaluation, (2008).
[6] ASTM E1820-13, Standard test method for measurement of fracture toughness, (2013).
[7] ISO 21307:2011(E): Plastics pipes and fittings – Butt fusion jointing procedures for polyethylene (PE) pipes and fittings used in the construction of gas and water distribution systems,(2011).
[8] Determination of tolerable size defect for butt-fusion welding in polyethylene gas pipes, KGS Internal Report, (2008).
[9] DVS 2203-2, Testing of welded joints between panels and pipes made of thermoplastics – Tensile test, (2010).
[10] ASTM D 1599-14ϵ1, Standard test method for resistance to short-time hydraulic pressure of plastic pipe, tubing, and fittings, (2014).

[11] H. S. Lai, S. H. Kil, K. B. Yoon, Effects of defect size on failure of butt fusion welded MDPE pipe under tension, J. Mech. Sci.Technol. 29 (2015) 1973−1980.

[12] M. Parsons, E. V. Stepanov, A. Hiltner, E. Bare, Correlation of fatigue and creep slow crack growth in a medium density polyethylene pipe material, J. Mater.Sci.35 (2000) 2659–2674.

[13] A. Shah, E. V. Stepanov, G. Capaccio, A. Hiltner, E. Baer, Stepwise fatigue crack propagation in polyethylene resins of different molecular structure, J.Polym.Sci. Pol. Phys. 36 (1998) 2355–2369.

[14] M. B. Barker, J. Bowman, M. Bevis, The performance and causes of failure of polyethylene pipes subjected to constant and fluctuating internal pressure loadings, J. Mater.Sci. 18 (1983) 1095−1118.

[15] C. Ruggieri, Further results in J and CTOD estimation procedures for SE(T) fracture specimens – Part I: Homogeneous materials, Eng.Fract. Mech. 79(2012) 245–265.

[16] M.Paredes, C.Ruggieri, Further results in J and CTOD estimation procedures for SE(T) fracture specimens – Part II: Weld centerline cracks, Eng.Fract. Mech. 89 (2012) 24–39.

[17] M. Parsons, E. V. Stepanov, A. Hiltner, E. Bare, Correlation of fatigue and creep slow crack growth in a medium density polyethylene pipe material, J. Mater.Sci. 35 (2000) 2659−2674.

[18] M. Parsons, E. V. Stepanov, A. Hiltner, E. Bare, Correlation of stepwise fatigue and creep slow crack growth in high density polyethylene, J. Mater.Sci. 34 (1999) 3315–3326.